Chromospheric Oscillations as a Probe of Structure and Energy Deposition in the Upper Solar Atmosphere

Summary of Personnel and Work Efforts

Scott W. McIntosh - Principal Investigator

Work commitment of 0.25 years for each of 3 years. Experienced in the analysis of remotely sensed solar data and, in particular, the understanding the observational interplay of chromospheric dynamics and the atmosphere in which they belong. Will be responsible for the coordination of this project, using previously archived observations or designing new multi-instrument/spacecraft observations to answer the questions posed, data analysis, reporting the results of the investigation to the community and preparing analysis for future observing platforms. Will perform the vast majority of the work proposed.

Mats Carlsson, Viggo H. Hansteen - Co-Investigators
(Institute of Theoretical Astrophysics, University of Oslo, Oslo, Norway)

Non-funded work commitment. Significant experience in studies linking chromospheric dynamics to transition region and coronal dynamics/energetics and the coupling of photospheric magnetic fields to the upper layers of the solar atmosphere. Will contribute to the data analysis software and the interpretation of data using forward modeling.

Bernhard Fleck - Co-Investigator
(Research and Scientific Support Department, European Space Agency, NASA/GSFC)

Non-funded work commitment. Considerable expertise in ground-based observation coordination and data analysis. Will assist in data reduction and Fourier analysis. Will be principally be responsible for reduction and interpretation of ground based observational components of this investigation.

Philip G. Judge, Bruce W. Lites - Co-investigators
(High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO)

Non-funded work commitment. Vast depth of expertise in chromospheric dynamics and magnetic field data analyses in both ground-based and space-borne observatories. Will contribute to the data analysis and interpretation of Stoke's profile and magnetic field data and dynamic coupling and application of methods to future observing platforms.

Theodore D. Tarbell – Co-Investigator
(Solar Physics Department, Lockheed Martin Space & Missiles, Palo Alto, CA)

Non-funded work commitment. Significant experience in the design, acquisition and analysis of photospheric/chromospheric ultraviolet and magnetic field measurements. Will contribute to the data analysis and the interpretation of TRACE and SOHO/MDI data.

Proposal Overview

Observations of oscillations in ultraviolet emission lines and continua formed in the solar chromosphere pose an important question: Given the ubiquity of chromospheric oscillations in atmospheric regions away from sunspots and large magnetic flux concentrations, what proportion of the wave energy is available to supply the quiet, ambient, upper chromosphere and corona with mass and energy?

In recent years, using observations obtained with *SOHO* and TRACE, we have been able to probe the temporal and spatial domains of chromospheric oscillations to a degree that was not possible from earlier ground-based observations. Recent work by the proposing team has demonstrated that understanding the interplay of the underlying magnetic field, its extrapolated/inferred topography and the observed spectroscopic quantities (continua, line intensities and Doppler velocities) is essential to understanding the dynamic nature of wave modes in the atmosphere. This research has found that identifying the region where the magnetic and hydrodynamic forces balance is critical to understanding the observed oscillatory signals. Tantalizingly enough, in the quiet Sun, this region lies in the mid-to-upper chromosphere, at the point where the temperature gradient begins to steepen.

Multi-dimensional MHD simulations performed by members of the proposing team have verified many of these observational results. They have demonstrated that significant amounts of wave mode conversion, dissipation and interference can take place in a realistic model atmosphere and, in particular, where the ratio of the hydrodynamic and magnetic pressures is of order unity. However, the role of radiative transfer processes in this region of the solar atmosphere cannot be overlooked when trying to understand these oscillations and the spectroscopic signals that we observe. A simultaneous effort by members of the proposing team is responsible for the coupling of detailed radiative transfer calculations to the MHD models. This will provide the final, vital, link to the self-consistent "forward-modeling" of solar conditions.

The proposed study is intended to be the observational counterpart to the MHD simulation and radiative transfer research being undertaken currently. Each of our existing observational datasets is rich with information about chromospheric oscillations on many spectral, spatial and temporal scales. Extracting, interpreting and drawing analogies between this information and that acquired from forward models give us a distinct advantage towards understanding the wave processes, their radiative coupling, and how they manifest themselves in observational datasets.

Over the duration of the proposed activities our primary objective will be to analyze and study archived data for comparison to specific simulated datasets. In situations where no previous observations exist, or the data do not provide a complete topographic picture of the plasma, we will use the experience gained from the previous analyses to design new observing programs combining data from existing space missions (*SOHO*, TRACE) with advanced ground based telescopes (Swedish Vacuum Solar Telescope II and the Advanced Stokes Polarimeter) to specifically address the problems relating to the dynamic and topographic nature of the solar atmosphere. We believe that the techniques discussed in this proposal will also offer insight into the analysis of data from forthcoming space missions, e.g., Solar-B and the Solar Dynamics Observatory.

We believe that this coupled analysis of observed and simulated data holds the key to understanding the manner in which mechanical energy emerging from beneath the photosphere is transported, deposited and constantly re-supplied to heat the ambient solar chromosphere and corona. The proposed research will offer a unique and comprehensive study of wave energy deposition at the base of the Sun-Earth Connection.

Scientific/Technical/Management Section

Section 1.1: Introduction

The Sun's atmosphere bathes the Earth and Solar System in particulate ejecta and electromagnetic radiation at almost all detectable wavelengths. The variation of these emissions, on scales of seconds to tens of years, has a great and direct impact on our local space environment. However, these variations are driven by poorly understood mechanical processes that we often associate with solar magnetic structure and its evolution over these typical temporal scales.

Understanding and quantifying the way in which mechanical energy emerging from beneath the photosphere is transported and deposited in the chromosphere, corona and solar wind above remains, quite possibly, the most significant hurdle blocking the progress of solar and heliospheric physics. This "coronal heating problem", as it is known, has existed since Edlén (1943) identified emission of nine times ionized iron from an eclipse observation. Edlén, with Biermann (1948) and Schwarzchild (1948), deduced that a mechanical heating flux (10^3 erg s^{-1} cm^{-2}) was required to maintain a mean ambient coronal temperature of $2x10^6$ K some three orders of magnitude hotter than the visible surface of the photosphere, radiating like a black body at some 5,500K. Understandably, because of this thermodynamic disparity, the corona has received a significant amount of attention in the literature (see, e.g., the recent review of coronal heating by Axford & McKenzie 2002).

The chromosphere, however, has been largely overlooked despite its richness in emission and structure. The variations of chromospheric structure over the solar magnetic activity cycle have been correlated to variations in UV radiation at the Earth (e.g., Viereck et al. 2001). The energy balance of the chromosphere is just as important as that of the corona since it spans many pressure scale heights linking the photosphere and corona, requiring about 100 times the mechanical energy flux required to heat and sustain the corona (Anderson & Athay 1989). This mechanical forcing must navigate through and support the energetic needs of the chromosphere before dealing with those of the corona. Cleary, there is also a "chromospheric heating problem".

The perceived observational proxy of this mechanical flux takes the form of quasi-periodic fluctuations in atomic, ionic or molecular chromospheric emission. We will refer to these fluctuations as "chromospheric oscillations".

In recent years, using the observations of the Solar and Heliospheric Observatory (SOHO; Fleck, Domingo & Poland 1995) and the Transition Region and Coronal Explorer (TRACE; Handy et al. 1998) we have been able to probe the domain of chromospheric oscillations (e.g., see Table 1 and Judge, Tarbell & Wilhelm 2001; Krijger et al. 2002) to a degree that was not possible from ground based observatories (see, e.g., Deubner & Fleck 1990). Recent publications (McIntosh et al. 2001; McIntosh & Judge 2002; McIntosh, Fleck & Judge 2003), using the observations of SOHO/TRACE Joint Observing Program (JOP) 72[1] have demonstrated that understanding the interplay of the underlying magnetic field, its extrapolated/inferred topography, and the observed quantities are

[1] The text description of JOP 72 is available online http://sohowww.nascom.nasa.gov/soc/JOPs/jop072.html

essential to understanding the passage of wave modes in the atmosphere. We have identified two basic configurations of the plasma topography that can significantly alter the observed imaging or spectroscopic signal observed. They are:

- The spatial location of the region where the magnetic and hydrodynamic forces balance, i.e. the plasma β (ratio of gas and magnetic pressures) is of order unity, is critical to understanding the oscillatory signals that are observed (McIntosh et al. 2001). Tantalizingly enough, in the quiet Sun, this region lies in the mid-to-upper chromosphere at a point where we can meaningfully supply mass and energy to the corona, see, e.g. Figure 1.
- Open and closed magnetic structures in the line-of-sight where magnetically isolated regions can effectively "quench" the chromospheric oscillations and UV intensities alike, see, e.g., Figure 2 (McIntosh & Judge 2002).

In a sense, the use of the observed oscillations to probe, uncover and understand the underlying plasma topography is a process that we dub, loosely, "chromo-seismology".

Table 1: Some SOHO/TRACE and ground-based observatory chromospheric dynamics campaigns. Shown are their JOP numbers. Instruments that are marked with an asterisk (*) were adversely affected by poor seeing or spacecraft problems.

Date (SOHO JOP #)	Duration (Hours)	Instruments	Target
1-4 October 1996 (46)	24 (Total)	MDI/SUMER/CDS/EIT	Quiet Sun, Disk Center
21-25 March 1997 (46)	30 (Total)	MDI/SUMER/CDS/EIT/ASP*	Quiet Sun, Disk Center
16 May 1998 (72)	2	MDI/ASP/TRACE/SUMER	Quiet Sun (x=-40, y=340)
17 May 1998 (72)	4	MDI/TRACE/SUMER	Active Region (x=-40, y=308)
26 February 1999 (72)	2	MDI/TRACE/SUMER/CDS	Quiet Sun, Disk Center
27 February 1999 (72)	2	MDI/TRACE*/SUMER/CDS	Coronal Hole, Disk Center
22 September 2000 (97)	2	MDI/TRACE/SUMER/CDS	Active Network(x=10, y=100)

These observational findings have been verified, and extended, to a large degree by the multi-dimensional magnetohydrodynamic (MHD) simulations presented by Rosenthal et al. (2002) and Bogdan et al. (2002, 2003). They have demonstrated that significant amounts of wave mode ducting, conversion, dissipation and interference can take place in realistic magnetic topologies[2] and when the ratio of the hydrodynamic and magnetic pressures is of order unity. Of course, as with all wide-reaching investigations as many questions have arisen as have been answered, yet having the MHD simulations of realistic magnetic topologies available to us provides a very important interpretative tool for the observational datasets.

Of particular interest to the observer upon seeing these simulations are the clear wave-mode interference patterns that are established in, and around, the regions of the magnetic topology studied. It can be said that the community researching chromospheric oscillations has largely overlooked the role of wave-mode interference in their observations. However, it is clear from the bullet points above that, "quirky" observational manifestations of the interplay of solar topography and spectroscopic quantities are commonplace and have been largely ignored by the community. Two commonly studied examples of solar phenomenology that may be subject to this observational misinterpretation are "running penumbral waves" (e.g., Nye & Thomas 1974) and "EUV blinkers" (e.g., Harrison 1997). As an example of using the MHD

[2] The plasma topography is the entire plasma environment of the atmosphere whereas the topology is the physical, magnetic structure that the topography adheres to.

simulations as an interpretative guide, in Section 1.6.3, we will briefly discuss why the interpretation of "running penumbral waves", inferred from the simulation presented in Bogdan (2003), may be a consequence of how they are observed and how the knowledge provided by the simulations can be used to guide a new observing strategy, which can prove, or disprove, this analysis.

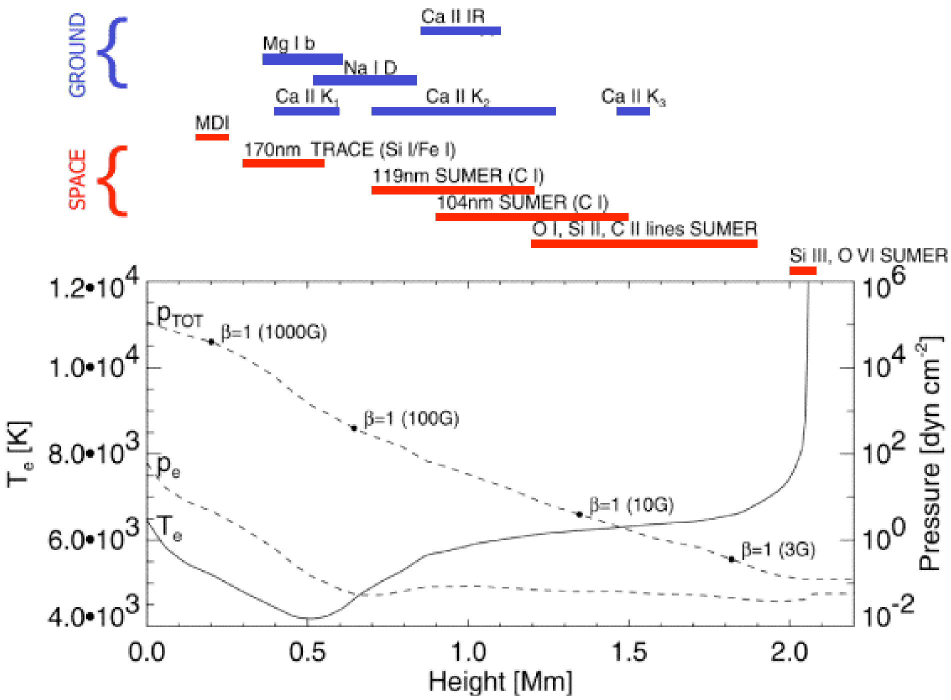

Figure 1: An overview of some of the thermodynamic parameters of the upper solar atmosphere (from the model atmosphere "C" of Vernazza, Avrett & Loeser 1981; hereafter VAL3C) and the formation layers of typical optical and UV lines from ground (blue) or space-based (red) observatories used to diagnose it. In the lower portion of the figure we show the model variation of the electron temperature (solid line), the electron pressure (lower dashed line) and the total plasma pressure (upper dashed line) with height. On the latter we indicate heights in a one-dimensional atmosphere where the plasma (ratio of total plasma and magnetic pressures) is one for the specific magnetic field strength (in parentheses).

The observational data analyzed and published to date by members of the proposing team (McIntosh et al. 2001; McIntosh & Judge 2002; McIntosh, Fleck & Judge 2003) have come from three one-hour long sequences from SOHO and TRACE. Therefore, there is a wealth of further information about chromospheric oscillations and their interplay with the surrounding medium available in archived data from these missions. To this end, we propose to continue to analyze archived observations using novel methods to probe the temporal, spatial, frequency, phase and spectral space spanned by chromospheric oscillations, cataloging the results in each case. We have the distinct advantage of having a data synthesis, "forward modeling", capability using the MHD simulations (eventually including detailed radiative transfer - RT - calculations) as an interpretative aid to what is inherently a poorly conditioned and ill-posed "inverse problem". In situations where the archived observational data is not complete in any of the domains mentioned above ("running penumbral waves" as an example) we will design new sequences for coordinated observation campaigns from space and ground-based observatories.

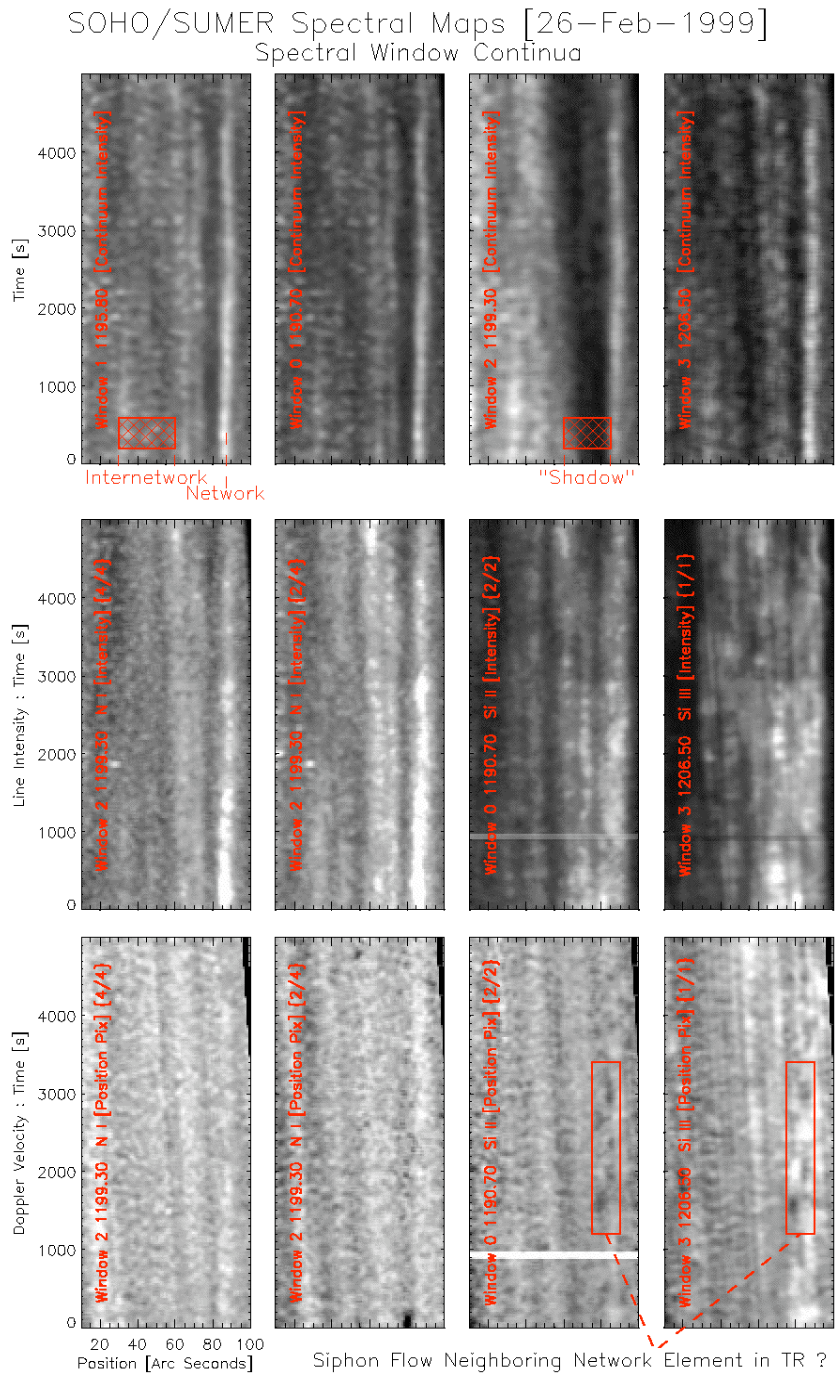

Figure 2: Selected Spectroscopic SOHO/SUMER Signals from the JOP72 dataset observed on February 26, 1999. The panels of the top row show the continua in each of the four observed spectral "windows". The presence of the "shadow", attributed by McIntosh & Judge (2002) to a closed magnetic region in the SUMER line of sight, centered around position 80, neighboring the network element at position 87, is clear as is its persistence with time. The central row of panels demonstrates the change in line intensity from lines fitted in the spectral windows; there are significant oscillation signal and morphological changes from the N I lines on the left to the Si III line on the right. The bottom row of panels show the measured Doppler velocities, oscillatory signal is prevalent, notice the persistent "siphon" flow in the two TR lines (Si II, Si III) on the right that is not present in the chromospheric N I lines; a possible observational indicator of a closed field region in the line-of-sight. Piecing these types of multi-wavelength information together cleary holds the key to understanding the underlying structure of the plasma. This figure is adapted from Fig. 1 of McIntosh & Judge (2002).

From the proposed analysis of multi-wavelength time-series observations of different topographic regions of the solar atmosphere we will gain the knowledge of wave processes (ducting, conversion, interference, dissipation) and how their identification depends critically upon our ability to accurately interpret the observed data. We will make use of state-of-the-art simulations, using realistic model plasma topographies (observationally determined magnetic topology with a photospheric driving oscillation) as a basis for the data interpretation in the temporal, spatial, frequency, phase and spectral domains. Using this "chromo-seismology" framework we will use data from existing and future observing platforms (e.g., Solar-B and Solar Dynamics Observatory) to understand the sustenance and heating of the solar chromosphere, and corona, at the seat of the solar wind and the Sun-Earth connection.

To summarize, we will:

- Reduce and analyze existing multi-wavelength time-series observations of the chromospheric plasma regions from SOHO, TRACE and ground-based observatories.
- Design and acquire new multiple platform observational datasets that span the spectral, spatial and temporal domains of the chromospheric plasma when they are required.
- Propose interesting candidate datasets and magnetic topologies for "forward" MHD modeling.
- Interpret the observational and simulated data using novel multi-scale techniques to understand the dynamic and energetic ramifications of the interplay of the observed oscillations and the plasma topography.

Section 1.2: Coordinating with Existing NASA OSS Proposals

Two existing NASA OSS studies by members of the proposing team are under way, within this solicitation we propose to undertake the last, missing, component of this triumvirate:

- "An investigation of Wave Propagation in the Magnetized Solar Atmosphere" (Thomas J. Bogdan, P.I., NRA-00-OSS-01-SECGI) evaluates the theoretical measure of the magnetic field on waves and oscillations in the model atmosphere through the analysis of advanced multi-dimensional magneto-hydrodynamics (MHD) simulations.
- "Radiation hydrodynamic synthesis of chromospheric data: a completion of the remote sensing process" (Philip G. Judge, P.I., NRA-01-OSS-01-SHP), realizes that placing the pieces of the complex chromospheric oscillation "jigsaw" puzzle together requires the coupling of MHD and detailed radiative transfer calculations (like those recently presented in Carlsson & Stein 2002) to theoretically model and understand the fluctuations in the electromagnetic radiation detected by space and ground-based observatories (see, e.g., Carlsson & Stein 1997).
- The missing component of this approach is the work described in this proposal. The dedicated analysis of observational data to complement, support and highlight the results of the MHD and RT analyses.

Integrating these first two tasks into full multi-dimensional MHD and RT, R-MHD if you will, computations is the overarching, long-term, goal of the project that was started several years ago at the High Altitude Observatory.

We propose to use existing archived multi-wavelength time-series data from SEC missions to probe and understand the role of the atmospheric topography on the observed chromospheric oscillations through a coupled spatial, temporal, spectral and phase domain analysis. This data acquisition and analysis effort will be coordinated in an iterative "forward" fashion to quantitatively compare the results derived from the observations with those from the integrated results of the detailed R-MHD computations using identical data analysis tools.

Section 1.3: "Chromo-seismology"

We propose to refine and integrate the analysis of large coordinated multi-wavelength solar imaging and spectroscopic time-series datasets (like those shown in Figure 2) to probe the photosphere, chromosphere, transition region, their physical connectivity and dynamic behavior. We hope for a similar picture to develop of the chromospheric plasma topography as Helioseismology has provided for the sub-photospheric thermodynamic structure since the launch of GONG network and SOHO (see, e.g., Christensen-Dalsgaard 2002).

Using the "chromo-seismology" approach, we will:

- Co-align and correlate multiple observing platform time-series observations that span the solar chromospheric plasma.
- Determine the underlying magnetic topology through the analysis of longitudinal (and vector, if available) magnetographs. Apply an atmospheric model (cf. VAL3C, or a more complex model as necessary) to construct the plasma topography.
- Use established Fourier-based and multi-scale time-frequency wavelet analysis of the observed data to spatially map and characterize the wave-modes present.
- Draw conclusions on the wave energy deposition through the analysis of the wave-modes spectral, spatial and temporal variations within the plasma topography.

In the following sub-sections we will illustrate some of the principal analysis methods of "chromo-seismology" through specific examples.

Section 1.3.1: Data Assimilation and Analysis

We propose to employ novel analysis methods to probe, map and understand the interplay of the chromospheric plasma topography and chromospheric oscillations from imaging and spectroscopic time-series data sets. This analysis will allow us to study the layers of the atmosphere where the oscillations can influence the support and heating of the plasma through mode-conversion, dissipation and other related mechanisms.

Using a blend of Fourier (power, phase-difference and coherence spectra) and wavelet (power and coherence spectra) based analysis techniques at many atmospheric locations we can construct a consistent map of the plasma's structure and connectivity.

With a multi-wavelength time-series that is of one-hour duration, like those shown in the figures contained in this proposal, we are able to build a spatial, temporal and spectral picture of oscillatory power and phase-differences in the chromosphere using a relatively straightforward Fourier analysis (McIntosh, Fleck & Judge 2003). Likewise, using a frequency-time wavelet analysis[3] (see, e.g., Torrence & Compo 1998) we are able to refine these calculations and study the intermittency of the wave-modes as, more often than not, they occur in small packets of a few periods or less in the network and inter-network plasma (e.g., Wikstol et al. 2000; McAteer et al. 2003). In Figure 3 we show a sample visualization obtained through a wavelet analysis of the 3.3 (±1; blue "cloud") mHz and 5.5 (±1; red "cloud") mHz wave-packets in the TRACE 1600 Å bandpass time-series obtained on September 22, 2000 as part of SOHO/TRACE JOP 97. Clearly these inter-network wave packets are temporally intermittent, from the structure of the "clouds" of wavelet power. That intermittency might pose a problem to accurate Fourier power map analysis because the packets of information will be smoothed by the action of the Fourier transform depending on the duration of the packet. Features of wavelet transforms, like obtaining spatial distributions of wave packet power, intermittency and mean frequency will be explored in parallel to the standard Fourier methods within the framework of the proposed research.

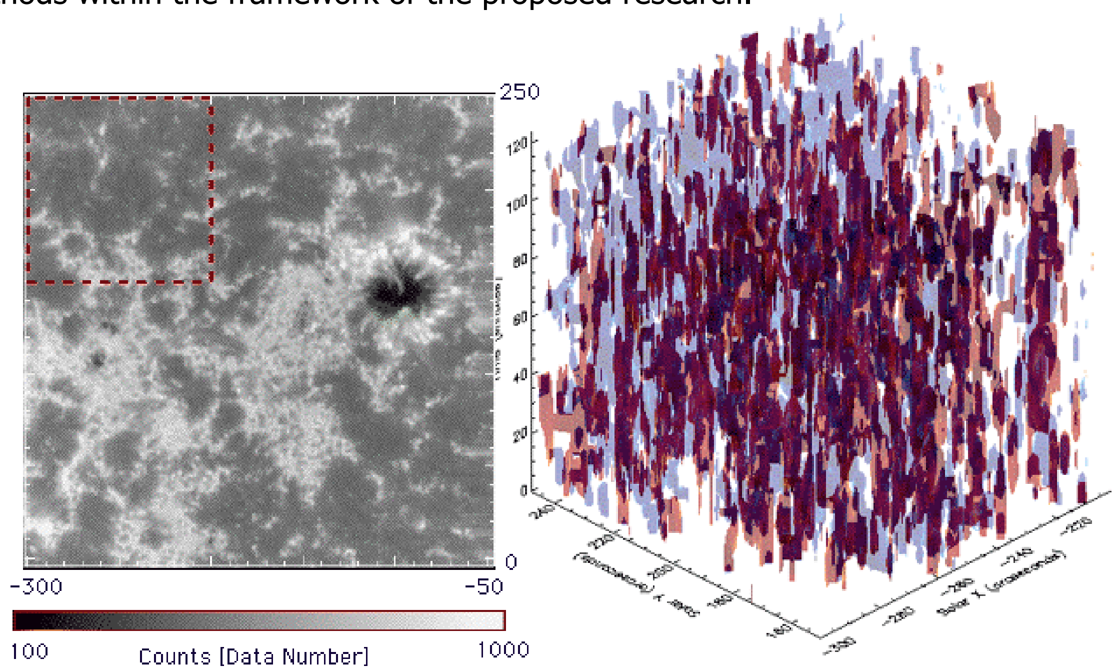

Figure 3: A visualization of Quiet Sun (region inside the red dashed boundary) wave packets in isolated 3.3mHz (~five minute period; blue) and 5.5mHz (~three minute period; red) frequency ranges. These wave packets are derived from a wavelet analysis of the two-hour duration 1600 Å bandpass time-series of TRACE taken on September 22, 2000. This "cloud" image is created by forming a wavelet transform of the time-series at each spatial pixel, isolating statistically significant (> 95% confidence) and rendering the resulting x, y, t volume in each frequency range. The intermittency of the quiet chromospheric wave packets is clear.

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[3] With the application of a wavelet transform to any time-series data there is an event localization in time and frequency space, the phase information is non-trivial to interpret. When phase-difference computations are required a Fourier phase analysis is preferred, although the former should be investigated.

We will discuss the data assimilation and analysis techniques below, by way of two examples, to highlight their applicability to achieving the proposed goal of probing the chromospheric structure and wave energy dissipation. These methods can be applied to provide a cross-analysis bridge between the observed data and those resulting from the parallel MHD (and eventually integrated RT) simulations.

Section 1.3.2: Quiet Chromosphere and Transition Region Structure

In the past, in the quiet solar chromosphere and transition region, it was presumed that the influence of the plasma topography on inter-network chromospheric oscillations was minimal. Indeed, a great deal of effort has been spent on the debate as to whether or not the quiet inter-network regions of the chromosphere are effectively free from the influence of the magnetic field (Carlsson & Stein 1998; Deubner 1998; Kalkofen 2001). Figure 2 demonstrates that dramatic variations can occur in the spectroscopic signals observed in the regions above and below the "magnetic transition zone", or "canopy" as it is often called, where β is of order unity. The presence, or lack, of significant power in the 3-8 mHz frequency range in the spectroscopic datasets is consistent with the interplay of the magnetic transition zone and the wave-modes present (McIntosh et al. 2001). In this case, the canopy is located somewhere between the formation heights[4] of the N I lines (~1.0Mm) and the Si II/III lines (~1.7Mm).

With the combination of magnetograms, Dopplergrams, continuum filtergram imaging time-series, provided by SOHO/MDI (Scherrer et al. 1995), and the UV continuum imaging time-series data of TRACE (in the 1550, 1600 and 1700 Å bandpasses) we are able to obtain a complimentary two-dimensional view of the magnetic transition zone. Using the MDI magnetogram, filtergram and TRACE bandpass time-series we can build "maps" of oscillatory power stepping upward through the atmosphere. These maps are constructed by accurate co-alignment and correlation of the time-series images for the signal, λ, into a cube $D_{\lambda}(x,y,t)$ such that the Fourier transform of that cube is itself a cube with the temporal dimension replaced by one of frequency ν, i.e., $f_{\lambda}(x,y,\nu)$. By choosing specific frequency ranges of interest and looking at the cross-power ($C_{12}(x,y,\nu) = f_{\lambda 1} \cdot f^{*}_{\lambda 2}$) and phase-difference spectra ($\Delta\phi_{12}(x,y,\nu) = \tan^{-1}[\mathrm{Im}\{C_{12}\} / \mathrm{Re}\{C_{12}\}]$) of different f_{λ} cubes one can asses the spatial dependence of diagnostic quantities like the integrated oscillatory power and phase-difference gradient, see Figure 4.

Close comparison of panel A of Figure 4 with panels B and C of shows the expansion of a dearth in oscillatory power, outward from network elements, that highlights the strong correlation between where the spectroscopic signal is formed and the plasma topography, through the plasma-β[5]. Going further, we can estimate the spatial phase-difference variations between the three TRACE UV bandpasses, see panel D. Again, there is a visually striking correspondence between regions of low phase-difference gradient and the proxy of the plasma topography.

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[4] Estimates of line, or continuum formation heights are taken from Vernazza, Avrett & Loeser (1981).

[5] The plasma topography in this case is derived from a simple potential extrapolation of the time-averaged longitudinal magnetic field and the use of the VAL3C model parameters to compute the plasma-β variation.

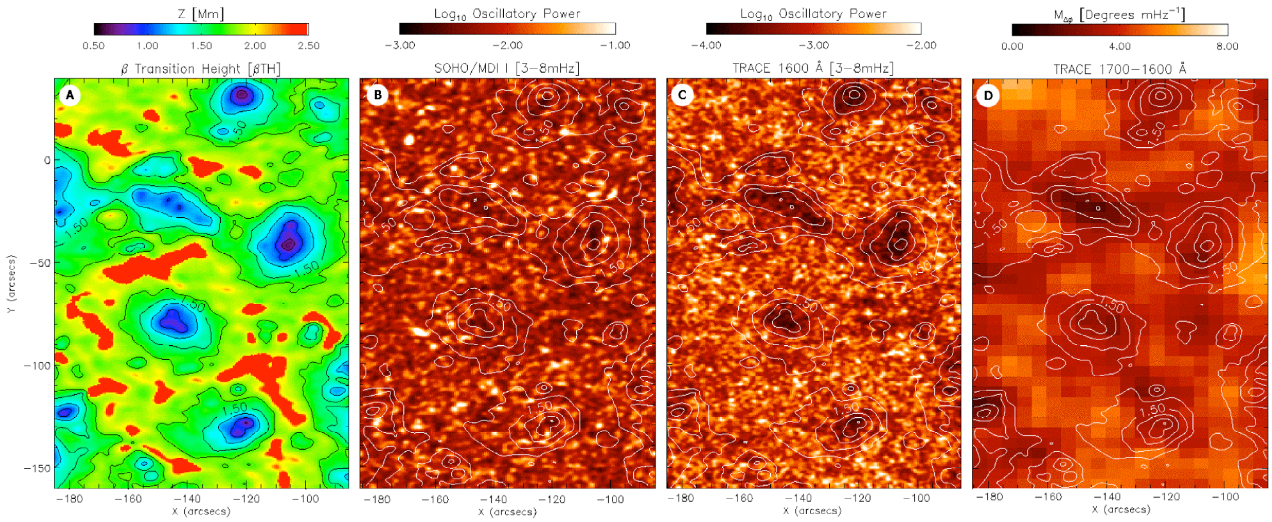

Figure 4: From left to right we show analysis of a portion of the TRACE observations of the February 26, 1999 run of JOP72 observations. In panel A we show the spatial distribution of heights where the plasma β, derived from a SOHO/MDI potential field extrapolation and the use of the VAL3C atmospheric model (Vernazza, Avrett & Loeser 1981), is of order unity; the overlaid contours are spaced by 0.25Mm, the dark regions identify locations of chromospheric network. Note the extension/spread of the green chromospheric "canopy" regions. Panels B and C show the spatial variation pf Fourier oscillatory power in the 3-8 mHz frequency range of the SOHO/MDI Ni I (6768 Å) continuum filtergram and the TRACE 1600 Å continuum bandpass, respectively. Note the correlation of the darkest points of the MDI continuum filtergram with the cores of the network elements and the drop in 1600 Å Fourier power away from the network elements. Panel D shows the variation of phase-difference gradient between the 1700 and 1600 Å bandpass time-series, again there is a more than passing correlation between regions of low phase-difference gradient and the "canopy" structures shown in Panel A. These panels are adapted from figures shown in McIntosh, Fleck & Judge (2003).

Explaining the latter correlation is relatively straightforward since the phase difference ($\Delta\phi$) between the two bandpasses can be approximated by $\Delta\phi = \left(\Delta z / V_p\right)\Delta\omega$, where Δz is the difference in the signal formation height, V_p is the phase velocity and $\Delta\omega$ is the change in frequency. So, in the case of phase-difference gradient, $M_{\Delta\phi} = \left(\Delta\phi / \Delta\omega\right)$, variations we have either,

The phase-difference changes indicate the reciprocal of the difference in phase-velocity of the oscillation as observed in the two bandpasses. It's spatial variation may indicate that waves with an infinite phase velocity, or standing waves, are isolated to regions in and around the network whereas waves of finite phase velocity are able to propagate upwards in the inter-network atmosphere. This is an important distinction to make.

Or, the phase-differences observed are a consequence of the overlapping in the TRACE bandpasses. In network regions the formation heights will be compressed and overlap substantially, in the inter-network there may be a significant separation in the bandpass formation heights.

These two explanations are intertwined in imaging data; without the Doppler velocity information provided by spectroscopic measurements, we will be hard-pressed to deconvolve these factors observationally. In cases where we wish to study the phase difference gradient relationships in the plasma topography we will add complementary ground-based observations from some of the lines shown in Figure 1, or instruments mentioned in Table 1. The additional information from these filtergrams will help decouple the TRACE bandpass observations. In addition, with the interpretative assistance provided by the combination of MHD and, eventually, detailed RT, simulations we will be in a position to understand if, and how the "canopy" causes the spatial phase-difference gradient patterns to appear.

Section 1.3.3: The Atmosphere Neighboring a Sunspot: Running Penumbral Waves?

This is just one example of where the MHD simulations can lead the observations to a possible break in the understanding of a long-standing interpretative problem in solar physics; what exactly is a running penumbral wave? Observed predominantly in H_{α} by means of their line-of-sight (LOS) velocity, they occur in almost every "steady" sizeable sunspot and show a steady progression of LOS velocity, radially outward in the spot, with a typical period between three and five minutes. Searches at the limb to observe the LOS velocity variations in projection have failed to reveal horizontal motions associated with the penumbral waves, so it is perceived that the variations are predominantly vertical in H_{α}.

An as yet unpublished analysis of wave fronts and patterns in synthetic time-series (at multiple heights in the model, spaced by 0.25 Mm) from the sunspot simulation presented in Bogdan et al. (2002, 2003) has revealed that significant spatially coherent and continuous interference patterns appear in the lower portions of their simulation, see Figure 5. These patterns appear at certain heights in the model and predominantly involve the passage and beating of stimulated "slow", generated "fast" magneto-atmospheric and acoustic wave modes with one another. Their appearance manifesting themselves as waves with a smooth transition from 30 km s^{-1} to 6 km s^{-1} in the LOS (vertical) model velocity spanning the outer edge of the model spot's to the outer edge of its penumbra. Interestingly, the continuity of the interference pattern breaks down with height and appears to be vertically localized between heights of 0.3 and 0.5 Mm in the model atmosphere. Now, bearing in mind that H_{α} is a broadband spectral image with a formation "layer" spanning many scale heights of the photosphere and chromosphere, we can imagine that the signal of this complexity could easily be interpreted as a single wave-mode.

A high spatial and temporal resolution study of this region, with considerably narrower spectral diagnostics may, or may not, show the fragmented structure of the perceived interference pattern. Within the framework of the proposed research project we will investigate features of this kind by designing detailed observations from the ground and space to spectrally span, with as little overlap as possible, the target region. Being able to decompose the complex interference in observational data using the knowledge of the wave-modes learned from simulations will mark a transition in our understanding of atmospheric oscillations and will help to provide an unambiguous picture of evolution of the observed wave modes as well as their energetic and dynamic interplay with the plasma topography.

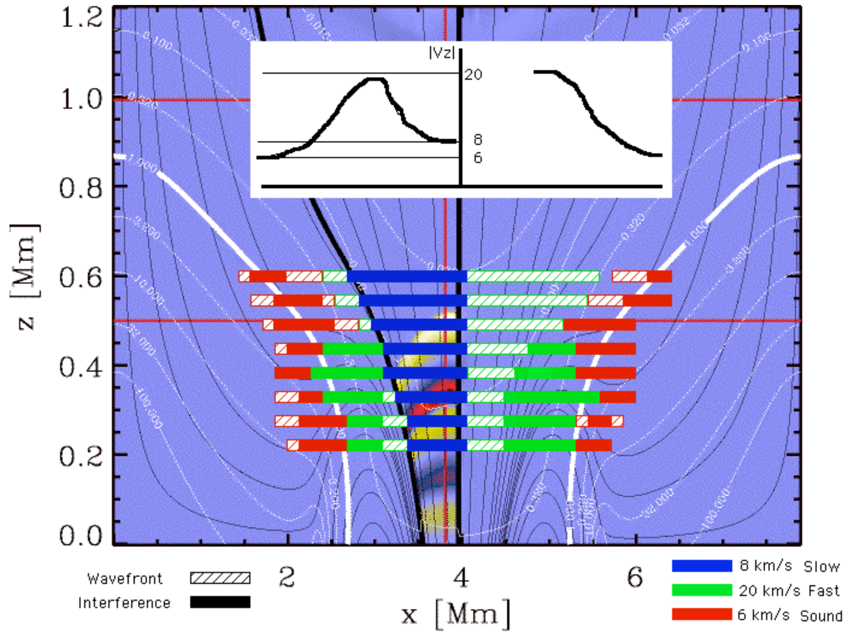

Figure 5: Qualitative analysis of the interference pattern that is established in one of the sunspot MHD simulations presented by Bogdan et al. (2002, 2003). In this case iso-contours of plasma β are in white, with β=1 thicker than the others and the iso-potentials, or field lines are shown in black. At heights, spaced by 0.25 Mm, we have formed, studied and classified synthetic time-series. The cross-hatched regions are where wave-modes travel without interacting with others, the solid regions mark interference zones of one mode with at least one of the other two generated in this simulation (blue; slow-mode, green; fast-mode, red; acoustic mode). At the model altitude of around 0.4 Mm we see that there is a continuous, strong, interference pattern established from the model spot's umbra and spanning its penumbra. Indeed, the velocity profile tracing outward across the penumbra (slow, then fast with a gentle drop to the sound speed at the very outer edge of the penumbra) and its variation with time is very reminiscent of the phenomena that is observed and dubbed a "running penumbral wave".

Section 1.4: Objectives of the Proposed Work

The overarching objective of the proposed research is to observe the electromagnetic emissions of the chromosphere and transition region, understand and interpret the oscillatory signals in a "forward" synthesis between observation and computational models to probe the structure and energy dissipation of the atmospheric topography. The specific constituents of this research goal are:

Determine and map the atmospheric topography from as many simultaneous time-series observations as possible of distinct solar features (e.g., quiet Sun, sunspots, active regions and coronal holes) using the methods outlined above. If the archived data are not sufficient to complete the proceeding tasks then we will design and acquire further SOHO/TRACE contemporaneous time-series observations, taking greater advantage of ground-based observatories, spectrograms and filtergrams to cover as many atmospheric layers in the target region as is possible.

Model the plasma topography using multiple magnetic field extrapolation methods and sources of longitudinal, or vector, magnetic field data in the photosphere to validate the topographic maps of the atmosphere.

Use novel wavelet and Fourier based data analysis techniques to examine the interplay of the observed oscillations and the topography of the plasma. How the plasma topography varies with time and how it channels, ducts, modifies and eventually dissipates oscillations in the 1-50 mHz frequency range in different atmospheric layers.
Iterate back with the coupled multi-dimensional MHD, and radiative transfer simulations when they become available, to cross-reference the imprint of the oscillations on the synthetic spectroscopic diagnostics with those observed.
The coupled approach of observational analysis and forward-modeled MHD simulations will allow us to draw conclusions on the wave energy deposition through the analysis of the wave-modes spectral, spatial and temporal variations within the plasma topography.

Section 1.5: Perceived Impact of the Proposed Work

We hope that the proposed work will lead to, through the detailed analysis and comparison between remotely sensed solar data and that from advanced modeling strategies:

A consistent and unified understanding of chromospheric oscillations in several, significantly different solar plasma topographies (e.g., quiet Sun, coronal holes and around active regions or sunspots).
Knowledge of the evolutionary path of propagating oscillations, from generation to dissipation, through these energetically important regions of the solar atmosphere.
Integrated analysis tools for the interpretation of the complex coupled multi-dimensional MHD radiative transfer simulations at some later date.
Provide an observational framework for investigations of this sort for the next generation of space-based solar observatories (Solar-B and the Solar Dynamic Observatory specifically).

Section 1.6: Relevance of Proposed Work

The proposed work directly addresses the Sun-Earth Connection Program's Strategic Goal II 1 "Understand the changing flow of energy and matter throughout the Sun, heliosphere and planetary environment", and specifically RFA (a) "Understand the structure and dynamics of the Sun and solar wind and the origins of magnetic field".

We propose to use data from the SEC SOHO and TRACE spacecraft, with support from ground-based observatories, to probe the structure and energy deposition in the solar atmosphere using the observed oscillations in the chromospheric and transition regions of the atmosphere. The outcome of the proposed work will lead to a greater understanding of one of the most overlooked regions of the solar atmosphere; the chromosphere. The electromagnetic radiation emanating from the solar chromospheric plasma has a profound effect on the heliosphere and, in particular, on the Earth's upper atmosphere and local space environment. This work will be complementary to two existing NASA OSS research efforts by other members of the proposing team, providing the observational understanding and evidence needed to explain their model results, and vice versa; closing the "conceptual loop" on chromospheric oscillations. This approach can offer significant inroads into the understanding of the wave processes, dynamics and energetics at the base of the Sun-Earth connection.

Section 1.7: General Plan of Work (Milestones)

Year 1: We will analyze the existing, coordinated SOHO and TRACE data, cataloging their features and characteristics. Interesting candidate samples will be put forward for MHD "forward" modeling. The results of the analysis will dictate the design of further investigations and observing strategies to bridge observational gaps or shortfalls. The PI will travel to Boulder to collaborate on the analysis of Advanced Stokes Polarimeter magnetic field observations in the context of this proposal.

Year 2: At this stage of the study we will create tools to perform identical analysis on the observational and simulation data; this approach will undoubtedly result in a clearer view of the observed plasma's topographic structure and energy deposition therein. We will coordinate SOHO, TRACE and ground-based observations in a concentrated campaign to reduce, co-align and perform analysis on these data using the methods discussed above. Again, we will assess what observations should be used as a basis for further forward modeling. The PI will travel to Oslo to collaborate on the forward synthesis of spectroscopic signals from the MHD models.

Year 3: The PI will travel to both Boulder and Oslo and the group will draw conclusions between the connection between the observational data and those derived computationally. We will report the results of the observations and the coordinated studies to the community at meetings and in journal publications.

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Facilities and Equipment

No special facilities or equipment are necessary for the completion of this proposal, the existing facilities already available to the PI and Co-I are sufficient.

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Education

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B. Sc. (Honors First Class) Mathematics and Physics — Oct. 1991 – Jun. 1995
University of Glasgow, Glasgow, Scotland
Department of Physics and Astronomy

Experience

NASA Goddard Space Flight Center, Greenbelt MD.
Universities Space Research Association, Research Scientist I — Feb 2003 – Present
- Analysis of SOHO and TRACE UV/EUV data.
- Modeling solar plasma topography through remote sensing.
- Study of Self-Organized Criticality in Solar Plasmas.
- Scientific Coordination/Planning of SOHO (CDS/EIT) observations

NASA Goddard Space Flight Center, Greenbelt MD. — Feb. 2001 – Feb. 2003
European Space Agency, External Fellow
- Analysis of SOHO and TRACE UV/EUV data.
- Studying MHD wave propagation in the solar atmosphere.
- Scientific Coordination/Planning of SOHO (CDS/EIT) observations
- Study of Self-Organized Criticality in Solar Plasmas.

NCAR High Altitude Observatory, Boulder, CO. — Jan. 1999 – Jan. 2001
Advanced Study Program, Post-Doctoral Fellow
- Analysis of SOHO and TRACE UV/EUV data.
- Solar UV/EUV remote sensing problems.
- Studying MHD wave propagation in the solar atmosphere.

Honors

European Space Agency (ESA) External Fellowship for research in Solar Physics (2001).
National Center for Atmospheric Research, Advanced Study Program Fellowship (1998).
M. K. Hunter Memorial Award for Research in Physics (1996). University of Glasgow.
Physics class prize (1992,1994). Physics Department, University of Glasgow
Mathematics class prize (1991). Mathematics Department, University of Glasgow

Skills

Expertise in the use of the Interactive Data Language (IDL) for data analysis
Computing (Languages) : F77, F90, C, C++, Java, Pascal, HTML, Flash.

Activities

Member of American Astronomical Society and American Geophysical Union.
Peer reviewer/referee for Astronomy & Astrophysics, Solar Physics and Experimental Astronomy Journals.

Scott W. McIntosh - Publications

2003 McIntosh, S. W., Poland, A. I. 2003,"*Loop Footpoint Dynamics*", Submitted to the Astrophysical Journal, April 2003.
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Education

Ph.D. Astrophysics, Uppsala, Sweden	June 1987
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Employment and Professional Experience

Chairman of the supercomputer time allocation for the Norwegian Research Council.	1999 - Present
Member of the European Space Agency Solar System Working Group	1999 - 2002
Director, Institute for Theoretical Astrophysics, Oslo	1997 - Present
Chairman of Reference Group for High Performance Computing, Faculty of Mathematics and Natural Sciences, University of Oslo.	1995 - Present
Professor, Institute for Theoretical Astrophysics, Oslo	1993 - Present

Honors Fellow of the Royal Norwegian Academy of Science and Letters since 1994.

Memberships International Astronomical Union

Relevant Publications

Carlsson, M., Stein, R.F., 2002, "Dynamic Hydrogen Ionization" Astrophysical Journal, 572, 626.
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Employment and Professional Experience

Professor, Institute of Theoretical Astrophysics, University of Oslo	1997-Present
Firsteamanuensis, Institute of Theoretical Astrophysics, University of Oslo	1995-1997
Scientific Planner and Associate Scientist for SOHO/SUMER	1995-Present
Responsible for Solar-B EIS "Quick-Look" Software	

Relevant Publications

Hansteen, V.H., Leer, E. & Holzer, T.E., 1997, "*The role of Helium in the outer solar atmosphere*", Astrophysical Journal, **482**, 498

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Research Scientist, University of Würzburg	1991-1993
ESA Study Scientist, Solar Orbiter Mission	
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Relevant Publications

McIntosh, S. W., Fleck B. & Judge P. G., 2003, "*Investigating the Role of Plasma Topography on Chromospheric Oscillations Observed by TRACE*", In press, Astronomy & Astrophysics (April 2003).

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Publications 54 in refereed literature, 14 invited review papers and more than 35 contributed papers at conferences.

Selected Publications

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Lead for Spectro-Polarimeter on Solar-B Focal Plane Package
US Principal Investigator for Sunrise Balloon Experiment
Co-Investigator on NASA OSO-8 Satellite

Relevant Publications

Lites, B. W., H. Socas-Navarro, A. Skumanich, and T. Shimizu, 2002, "*Convergent flows in the penumbra of a delta-sunspot*", Astrophysical Journal, **575**, 1131
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Co-Investigator, SOI-MDI on SOHO
Co-Investigator, TRACE
Co-Investigator, Solar-B Focal Plane Package
Co-Investigator, SECCHI on STEREO
Co-Investigator, HMI on Solar Dynamics Observatory

Relevant Publications

Shimizu, T., et al., 2002, "*Photospheric Magnetic Activities Responsible for Soft X-Ray Pointlike Microflares*", Astrophysical Journal, **574**, 1074

Krijger, J. M, Rutten, R. J., Lites, B. W., Straus, Th., Shine, R. A. ,Tarbell, T. D., 2001, "*Dynamics of the solar chromosphere. III. Ultraviolet brightness oscillations from TRACE*", Astronomy & Astrophysics **379**, 1052

Judge, P.G., Tarbell, T.D. & Wilhelm, K., 2001, "*A Study of Chromospheric Oscillations Using the SOHO and TRACE Spacecraft*", Astrophysical Journal, **563**, 424

Ryutova, R. & T.D. Tarbell, 2000, "*On the Transition Region Explosive Events*", Astrophysical Journal, **541**, L29

Handy, B.N., Acton, L.W., Kankelborg, C.C., Wolfson, C.J., Akin, D.J., et al. 1999, "*The Transition Region and Coronal Explorer*", Solar Physics, **187**, 229

Current and Pending Support

Scott W. McIntosh

Current Support

NRA-01-OSS-01-SHP, "Novel Approaches to Spectroscopic Measurements: Observations, Simulation and Theory" (Jack Ireland - Principal Investigator) unfunded Co-I, awarded 10/09/2002.

Pending Support

NRA-02-OSS-01-SHP, "Rapid Acquisition Imaging Spectrograph Experiment" (Donald M. Hassler - Principal Investigator), unfunded Co-I.

AO-OSS-03-02, "Normal incidence EXtreme Ultraviolet Spectral Imager" (Joseph M. Davila - Principal Investigator), unfunded Co-I.

NRA 03-OSS-01-SECGI, "Using Observed Chromospheric Oscillations to Study the Topographic Structure and Wave Energy Deposition in the Upper Solar Atmosphere" - **$111K**- This proposal.

Co-Investigator Commitment Letters

12-MAI-2003 17:52 FRA ASTROFYS. INSTITUTT UIO TIL 0-0013012860264 S.02/02

UNIVERSITETET
I OSLO

To whom it may concern

Institutt for teoretisk astrofysikk
Postboks 1029 Blindern
0315 OSLO
Oslo

Telefon: 22856501
Faks: 22856505

Oslo, 12. mai 2003

I acknowledge that I am identified by name as a Co-Investigator to the investigation entitled "Chromospheric Oscillations as a Probe of Structure and Energy Deposition in the Upper Solar Atmosphere" that is submitted by Scott W. McIntosh to NRA 03-OSS-01-SECGI Sun-Earth Connection Guest Investigator Program NASA Research Announcement, and that I intend to carry out all responsibilities identified for me in the proposal. I understand that the extent and justification of my participation as stated in this proposal will be evaluated during peer review in determining the merits of the proposal.

Sincerely

Mats Carlsson

Mats Carlsson
Telefon: +47-22856536
E-post: Mats.Carlsson@astro.uio.no

TOTAL SIDER02
MAY 12 '03 10:20 22856505 PAGE.02

UNIVERSITETET I OSLO

To whom it may concern

Institute of Theoretical Astrophysics
P.O.Box 1029 Blindern
N-0315 OSLO
Norway
Oslo

Telephone: +47-22856501
Fax: +47-22856505

Oslo, 15th May 2003

Statement of Commitment

I acknowledge that I am identified by name as a Co-Investigator to the investigation entitled "Chromospheric Oscillations as a Probe of Structure and Energy Deposition in the Upper Solar Atmosphere" that is submitted by Scott W. McIntosh to NRA 03-OSS-01-SECGI Sun-Earth Connection Guest Investigator Program NASA Research Announcement, and that I intend to carry out all responsibilities identified for me in the proposal. I understand that the extent and justification of my participation as stated in this proposal will be evaluated during peer review in determining the merits of the proposal.

Sincerely

Viggo Hansteen

Viggo H. Hansteen
Telephone: +47-22856120
e-mail: Viggo.Hansteen@astro.uio.no

esa

MEMO

date/*date* 12 May 2003	ref./*réf.* SH/bf/03101		page/*page* 1/1
from/*de* Dr. Bernhard Fleck SOHO Project Scientist		visa/*visa*	
to/*à* Dr. Scott W. McIntosh NASA/GSFC		copy/*copie*	

subject/*objet* **SEC GI proposal "Chromospheric Oscillations as a Probe of Structure and Energy Deposition in the Upper Solar Atmosphere"**

To whom it may concern,

I acknowledge that I am identified by name as a Co-Investigator to the investigation entitled "Chromospheric Oscillations as a Probe of Structure and Energy Deposition in the Upper Solar Atmosphere" that is submitted by Scott W. McIntosh to NRA 03-OSS-01-SECGI Sun-Earth Connection Guest Investigator Program NASA Research Announcement, and that I intend to carry out all responsibilities identified for me in the proposal. I understand that the extent and justification of my participation as stated in this proposal will be evaluated during peer review in determining the merits of the proposal.

Sincerely,

Dr. Bernhard Fleck
SOHO Project Scientist

European Space Agency
Agence spatiale européenne

SOHO Project Scientist Office
NASA/GSFC Mailcode 682.3 Greenbelt, MD 20771
Tel: (301) 286-2455 Fax: (301) 286-0264
bfleck@esa.nascom.nasa.gov

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May 14, 2003

To Whom It May Concern,

We acknowledge that we are identified by name as Co-Investigators to the investigation entitled "Chromospheric Oscillations as a Probe of Structure and Energy Deposition in the Upper Solar Atmosphere" that is submitted by Scott W. McIntosh to NRA 03-OSS-01-SECGI Sun-Earth Connection Guest Investigator Program NASA Research Announcement, and that we intend to carry out all responsibilities identified for us in the proposal. We understand that the extent and justification of our participation as stated in this proposal will be evaluated during peer review in determining the merits of the proposal.

Sincerely,

Bruce Lites
High Altitude Observatory
National Center for Atmospheric Research

Phil Judge/bna
Phil Judge
High Altitude Observatory
National Center for Atmospheric Research

MAY-12-2003 18:21 SOLAR&ASTROPHYSICS 650 424 3994 P.02/02

LOCKHEED MARTIN

Lockheed Martin Space Systems Company
3251 Hanover Street
Palo Alto, CA 94304

11 May 2003

Dr. Scott W. McIntosh
USRA NASA/GSFC
Code 682.3
Greenbelt, MD 20771

Subject: NASA Guest Investigator Proposal

Dear Scott:

I acknowledge that I am identified by name as a Co-Investigator to the investigation entitled "Chromospheric Oscillations as a Probe of Structure and Energy Deposition in the Upper Solar Atmosphere" that you are submitting to NRA 03-OSS-01-SECGI Sun-Earth Connection Guest Investigator Program NASA Research Announcement, and that I intend to carry out all responsibilities identified for me in the proposal. I understand that the extent and justification of my participation as stated in this proposal will be evaluated during peer review in determining the merits of the proposal.

I look forward to working with you and our colleagues on this exciting project.

Sincerely,

T. D. Tarbell

Dr. Theodore D. Tarbell
Solar & Astrophysics Laboratory
Org. L9-41, Bldg. 252
Advanced Technology Center

MAY 12 '03 21:14 650 424 3994 TOTAL P.02
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